

0.1 Calorimeters and Targets

0.1.1 Overview

One of the main goals of MINER ν A is to improve the estimate of the incident neutrino energy based on the visible energy. The physics goals of MINER ν A require measurement of the energies of charged (p , $\pi^{+/-}$, $K^{+/-}$, $\mu^{+/-}$ and neutral π^0 , K^0 particles with energies up to a few GeV. The best way to do this would be with a fully active detector with 100% containment of the energy, but cost and location constraints prohibit a fully active detector of the required size. Instead, we have chosen a mixture of detectors with fairly standard elements.

The elements of MINER ν A are: a central fully active detector, an array of alternating lead and scintillator downstream and surrounding the active detector for electromagnetic calorimetry, an array of alternating steel and scintillator downstream and on the outside of the detector for hadron calorimetry, and plates of lead, steel, and carbon upstream of the central detector for upstream electromagnetic and hadron calorimetry.

Another goal of MINER ν A is to study the A dependence of neutrino interactions. The main detector is scintillator, which will serve as a carbon target. The upstream targets of iron, lead and some pure carbon, which serve as the upstream calorimetry, will do double duty as the nuclear targets.

The general criterion for the calorimetry is that hadronic energy and electromagnetic showers originating in the central tracking region should be fully contained. This is most critical for the downstream calorimetry because for the neutrino energies of interest the particle production is strongly peaked in the downstream direction and those particles have the highest energy.

The requirement that the upstream elements do double duty as both calorimeters and nuclear targets, means that care must be taken to allow them to serve effectively in both roles.

0.1.2 Electromagnetic Calorimeters

The detection of high energy photons is through the pair-production/bremsstrahlung process leading to a shower of e^+ , e^- and γ . Because the pair production cross section is proportional to Z^2 , lead sheets are generally used to produce a shower of reasonable length. The characteristic length of the shower varies with energy, but for photons up to a few GeV, as expected in our energy regime, 99% of the energy will be contained within 4 cm of Pb (about 7 radiation lengths).

The downstream electromagnetic calorimeter will consist of 20 layers of Pb, each 2 mm thick, interleaved with one layer of scintillator, consisting of the standard 1.7 cm thick layer of triangular strips. Arrangements such as this have been widely used in the past. The expected energy resolution is approximately $6\%/\sqrt{E}$, with E in GeV.

The side calorimetry is quite similar. Trapezoidal sheets of Pb, also 2 mm thick, will be interleaved with each layer of scintillator. The sheets will extend 15 cm into the active area. Photons entering the side calorimeter will be fully contained for angles less than about 25° with respect to the neutrino beam axis. At larger angles the shower will not be fully contained, but will penetrate into the outer hadron calorimetry, where the remainder of the shower will be fully contained, but less well sampled, leading to a decline in resolution.

Because the primary purpose of the upstream Pb/Fe/C plates is to serve as nuclear targets, the design does not allow as efficient calorimetry as the downstream and side modules. The sampling is more coarse because the Pb/Fe/C plates are thicker than in the downstream calorimeter. The arrangement of targets means that the number of radiation lengths the shower sees before escaping from the upstream

end will vary from 5 to 10. However, since the backward going photons will generally be much lower energy, showers starting in the active central region will be fully contained.

0.1.3 Hadron Calorimeters

The downstream hadron calorimetry will consist of 10 layers of iron, each 2.5 cm thick, interleaved with layers of scintillator, downstream of the electromagnetic calorimeter. The combined thickness of the 4 cm of Pb and 25 cm of Fe will stop muons up to about 300 MeV and protons of at least 500 MeV. One nuclear interaction length is 16 cm for Fe, so protons (or pions), so higher energy protons will also generally be stopped.

The side hadron calorimeter consists of a plates of iron 55.9 cm thick, with fives slots, each 2.5 cm wide, filled with scintillator. The total iron thickness is 43.4 cm, or 340 g/cm^2 , which can stop, from ionization losses alone, up to 750 MeV protons at 90° and nearly 1 GeV protons entering at an angle of 30° .

The resolution of the hadron calorimeter, based on studies by MINOS, is expected to be about $50\%/\sqrt{E}$ for hadron energies above 1 GeV. The resolution for lower energy particles is expected to be 50% or less, depending on the energy. The primary reason for the poor resolution is the likely interaction of the particle with a nucleus before stopping, which frequently produces one or more energetic neutrons whose energy is unobserved, making it difficult to get good energy resolution

As with the upstream electromagnetic calorimetry, the upstream hadron calorimetry relies on the nuclear targets, with a less efficient design than the downstream calorimeter. The upstream mass thickness is sufficient to stop protons originating in the active central region of at least 300 MeV.

Studies show that the visible hadronic component of quasi-elastic and resonant events originating in the fully-active central region of the detector are completely contained, apart from secondary neutrinos and low-energy neutrons. Figure 1 shows the fraction of escaping visible hadronic energy for deep-inelastic reactions in several hadronic energy ranges, and figure 2 shows the probability that a deep-inelastic event will leak visible energy as a function of the true hadronic energy. Only for hadronic energies greater than 8 GeV is there any significant probability of leakage and only above 15 GeV is the average fraction of escaping energy greater than 10%. The fraction of deep-inelastic interactions with hadronic energies over 15 GeV in the low-energy, medium-energy, semi-medium or semi-high energy beams is $< 1\%$, and so visible energy leakage should be insignificant. These estimates ignore downstream components beyond the forward hadron calorimeter, such as the MINOS detector, and are therefore conservative.

To study MINER ν A's calorimetric E_h resolution, the detector response to a neutrino sample generated throughout the inner detector by NUANCE, on carbon and hydrogen targets, was simulated using GEANT3. From this simulated sample, events where all hadronic fragments were contained within MINER ν A were used. Hits from lepton tracks in charged-current interactions are excluded from the following analysis.

In a fully-active scintillator calorimeter, the total light yield should be essentially proportional to E_h . (The proportionality is not unity due to escaping neutrinos, rest masses of charged pions, nuclear binding energy in the initial and secondary reactions and other nuclear effects such as pion absorption.) While the central inner detector volume is fully active, there are also regions with passive iron or lead absorber sandwiched between scintillators. In these sampling calorimeter regions, not all energy deposited results in scintillation light, so the light yield is corrected accordingly.

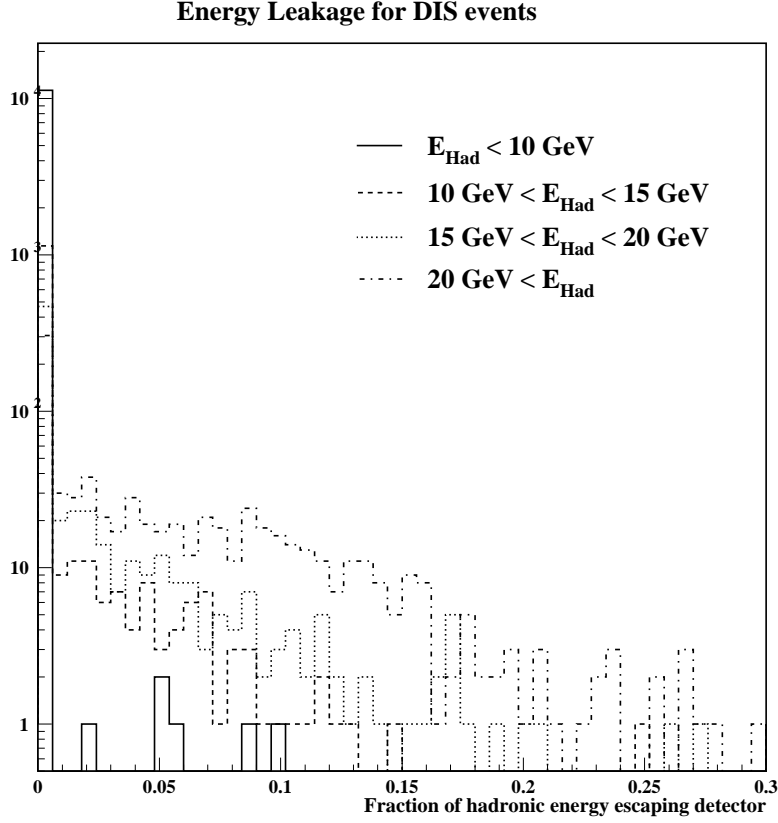


Figure 1: Fraction of hadronic energy escaping the detector for deep-inelastic scattering in the fully-active central region.

0.1.4 Nuclear Targets

The MINER ν A nuclear targets will consist of carbon, iron, and lead. Hydrogen is also present as a component of the scintillator in the active target. However, separating reactions on hydrogen from those on carbon will be extremely difficult and dominated by systematics. Iron is chosen both as a relatively inexpensive medium mass target and as the absorptive material used in many neutrino detectors, such as MINOS. Lead is the highest nuclear mass material that is easily obtainable.

There are a number of criteria that determined the nuclear target design. The ideal arrangement of nuclear targets would have many thin targets with several tracking layers in between each target in order to determine multiplicity of final states and the amount of energy going into relatively low energy particles. There are a number of factors which limit the number and size of targets, as well as the number of tracking layers.

The intrinsic spatial resolution of the detector is of order 1 cm, so thinner targets will be inefficient. MINOS used 2.5 cm iron plates, so plates thicker than this will not allow significant improvement of the knowledge of the low energy particle spectrum, which is one of the goals of MINER ν A. In order to get sufficient statistics over a wide range of kinematics, we would ideally like of order 1 ton of each target. The number of frames required to determine a single stereo point is two (an XU and an XV). We would at least two of these points, or four frames, between targets in order to determine the trajectory of short

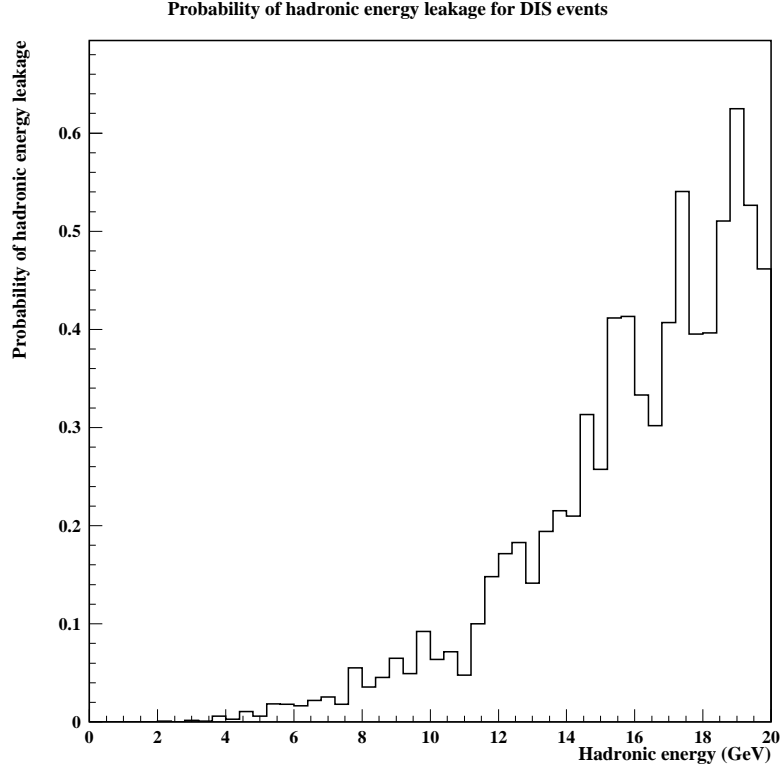


Figure 2: Probability that visible hadronic energy from a deep-inelastic event escapes undetected vs. total hadronic energy.

tracks before they enter the next detector. A thickness of 4 frames will stop a straight going proton of 200 MeV. However, because we wish to use MINOS for muon identification, we cannot put too many tracking planes between target plates or use too many plates since the upstream target will then be too far from MINOS a large fraction of the muons will miss MINOS. In addition, we would like to have similar detection configurations for each of the three materials.

The design we have decided on is shown schematically below, with the most upstream section on the left. Each “F” represents one frame, either an XU or XV, and an “FF” pair will be a set of XUXV.

FF Pb/Fe [1] FFFF Pb/Fe [2] FFFF Pb/Fe/C [3] FFFF Pb [4] FFFF Pb/Fe [5]

Targets [1] and [2] will be 2.5 cm thick Pb and Fe mounted in one plane. The areal coverage will be 60% Fe and 40% Pb, which gives about 230 kg of Pb and Fe in each target within a radius of 80 cm. Target [3] will have areal coverage of 50% C, 30% Fe, and 20% Pb, which gives 140 kg of C and 110 kg each of Pb and Fe. The Pb and Fe targets will again be 2.5 cm thick, and the C target 7.5 cm thick. Target [4] will be 0.75 cm thick pure lead, with a mass of 170 kg. Target [5] is 1.25 cm thick Pb and Fe, again 60% areal coverage in Fe and 40% in Pb, with a mass of about 115 kg each.

The total mass of Fe and Pb are 685 kg and 855 kg, respectively. The expected number of CC events are about 2.0 million for Fe, 2.5 million for Pb, and 400,000 for C.

The first two frames will allow us to determine if a particle going through the upstream veto detectors originated in the first nuclear target or outside the detector.

Targets [1] and [2] will have the Pb and Fe rotated with respect to each other to allow checks for

differences in detection.

Target [3] contains all three nuclei with essentially the same detection capability to allow detailed studies of the A dependence of interactions.

Target [4] is pure lead to insure that any produced photons, either from the upstream or downstream targets, begin to shower. The Pb sheet is about 1.5 radiation lengths thick, which is enough to begin the shower but not enough to contain it.

Target [5], directly upstream of the fully active central detector, will give allow us to study multiplicities and distributions of lower energy particles with good tracking and energy resolution.

We have studied this arrangement with our standard Monte Carlo. We find that it satisfies most of our requirements. Most importantly, energy containment for events originating in the central detector is good for upstream (backward) going particles despite there being less material, due to the fact that the backward going particles are lower energy. The energy of charged hadrons and photons from neutral meson decay resulting from quasi-elastic and resonance reactions is almost 100% contained, due to the very forward peaked nature of these reactions. For the most upstream nuclear target, energy confinement is worst for DIS reactions. The high multiplicity of these events produces some lower energy particles going upstream. However, over 90% of produced protons and charged pions are fully contained. Only photon containment is significantly worse than the central region. For incident neutrino energies above 2 GeV about 80% of the photon energy is contained. Thus we conclude that all targets can be used for studies of all interaction types at all energies with only moderate loss of resolution due to lack of confinement.

